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13. ABSTRACT *(Maximum 200 words)*

Millimeter-wave quasi-optical power combining schemes employing new and innovative architectures have been investigated with the objectives of building efficient arrays and addressing the specific shortcomings encountered during development. The importance of broadband wireless applications has been recognized through the implementation of array modulation schemes, taking into consideration noise, linearity and other relevent issues. Novel quadrature phase locked loop techniques for generating QPSK, 16-QAM and high order QAM modulation schemes have been developed. Omni-directional arrays using modified Vivaldi antennas, a monopole based Ku-band amplifier array with a gain of 5.4 dB, a Fabry-Perot resonator coupled oscillator array, an inclined plane horn antenna array and three-dimensional grating array strucures were investigated. Grating array structures, utilizing radiating waveguide apertures, offer low-loss free-space to circuit transitions, very large bandwiths, effective circuit isolation and good thermal dissipation properties.

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Second Generation Quasi-Optical Combiners

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Authors:

Richard C. Compton, and Warren Wright

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2. Table of Contents

4.A Problems Studied

With the support of the Army Research Office, Compton has investigated original and innovative schemes for millimeter-wave quasi-optical power combining and has investigated fundamental requirements of broadband wireless communication links employing such schemes.

The technical obstacles to be overcome for the implementation of such links include the development of combined solid state sources with sufficient power to compensate for the losses inherent in millimeter wave systems and the strict linearity requirements for multichannel digital coding schemes. Low cost, high power millimeter-wave sources with digital wireless capability are required for military as well as commercial applications. These applications have significantly different requirements with respect to bandwidth, range, gain, noise, packaging and modulation criteria than radar/seeker applications. Compton's investigations have covered significant aspects of these requirements; many of the problems inherent in meeting a particular set of requirements are only apparent when a power combining scheme is implemented.

Compton has investigated promising new schemes suitable for arrays of solid state millimeter wave devices.

- Omni-directional oscillator arrays, suitable for 360° (in the horizontal plane) coverage or sectoral coverage, have been developed. A daisy chain locking scheme was employed and binary-FSK modulation of a 28 GHz array was demonstrated. Significant improvements on radiation pattern quality and EIRP were achieved during the course of array development. An array phase-noise model under injection locking operation was also developed.

- The microstrip monopole probe planar array approach has been realized at Ku-band

in a 3 x 3 amplifier array. A modelling technique has been developed for the extraction of s-parameters for such quasi-optical planar periodic array structures.

- A quasi-optical scheme using a planar array of oscillators in a resonant Fabry-Perot cavity has been assessed.

- A quasi-optical n x 1 amplifier array concept using linear taper parallel plate horn antennas is being developed. The structure for this device consists of two back-to-back horn antennas which are joined by a narrow gap parallel plate section in which is situated the n x 1 circuit array.

- A new concept in millimeter wave achitecture based on a 3-dimensional grating structure is under development. This approach is proving to be particularly promising - offering very large bandwidths, good heat sinking capabilities for power devices, efficient coupling to free space beams, good circuit isolation and flexible circuit accommodation.

With these second generation power combining schemes Compton has investigated modulation schemes suitable for oscillator arrays and has developed novel quadrature phase locked loop techniques for generating Q-PSK, 16-QAM and high order QAM modulation schemes.

4.B Summary of the Most Important Results

V-band and W-band Oscillators (Mark Vaughan/Martin Marietta)

V-band [20] and W-band [1] oscillators with frequency and output power relatively insensitive to device variations due to fabrication tolerances were designed by Cornell. These oscillators were then fabricated monolithically by Martin Marietta using 0.1 μm pseudomorphic HEMT technology. Both designs use a pair of resonant Tees [21] in the double source circuitry of the HEMT which reduces the dependence of the oscillating frequency on the HEMT parameters. The rf output of the device is fed to an E-field probe which

protrudes into a waveguide.

For the 60 GHz oscillator several design iterations were made in both microstrip and coplanar waveguide with the latter design offering better performance due to the superiority of the fabrication. The 60 GHz CPW oscillator design produced 25 mW with a dc-to-rf efficiency of 11%.

The 77 GHz design was implemented in CPW, was similar to the 60 GHz design but featured varactor tuning incorporated into the gate circuit. Only one design iteration was performed and the HEMT finally used in the fabrication was of a slightly different type than that used in the design. The resultant output power was 0.3 mW and the varactor tuneable 3 dB bandwidth was 230 MHz.

Extensive modelling of these oscillators was performed using a very detailed rf equivalent circuit for the HEMT which enabled the weak points in the fabrication procedures to be identified. This modelling effort also led to strategies to further improve performance.

Omni-Directional Oscillator Arrays (Mark Vaughan)

A unique oscillator array, which is suitable for creating omni-directional or sectored transmitters in the azimuthal direction and with 10° - 20° elevation beamwidth, has been implemented [2, 18]. This planar array is polygonal in shape with an oscillator and endfire antenna in each sector radiating radially outwards with the beam confined near the plane of the array. Array development occurred via several iterations beginning with single sector devices using hybrid techniques. An X-band single FET oscillator was built in CPW which used a slotline fed Vivaldi antenna. An improved version at 10 GHz used a modified Vivaldi antenna and produced 24 mW with a dc-to-rf efficiency of 17%. These designs require no separate bias lines (for zero gate-source bias operation) since the CPW/slotline configuration allows drain-source biasing across the two slotline conductors.

The basic design was scaled to 28 GHz and its expected performance in an array was modelled. This led to an omni-directional design featuring 12 oscillator sectors (30° per sector) which were locked together via a daisy chain slotline coupling scheme from one oscillator sector to the next. A number FET oscillators and two or three element arrays were developed [4], using General Electric pseudomorphic HEMTs. This proved necessary to overcome the severe difficulties encountered in getting a full 12 sector array to have good locking characteristics. The individual oscillators had a wide locking range, 500 MHz, and the spread of the free running frequencies of the oscillators caused by fabrication variability was kept to within a 100 MHz span.

In the final version of the 28 GHz 12 sector array [5] all oscillators remained locked over the entire drain bias range (0.6 v to 2.5 v) and from extensive antenna pattern measurements (bias = 2 v), the total radiated copolar power was found to be 144 mW (EIRP = 0.28 W) with a combining efficiecy of 87% and a dc-rf efficiency of 11.6%. Improvement of the elevation pattern was achieved by placing circular metal disks above and below the plane of the oscillator array [6]. This technique reduced the elevation beamwidth from 60° to 10 - 20 ° with an increase in EIRP to 0.70 Watts and a directivity gain of 9.6 dB. This array was later used in a wireless communications demonstration utilizing binary frequency shift keying (FSK) as the modulation technique [14].

The omni-directional sector array has the phase centers of each radiating source situated at a radius of 20.5 mm from the center of the array and spaced 30° in the azimuthal direction. This leads to variations in radiated power in the azimuthal direction. This azimuthal ripple can be greatly reduced by bringing the phase centers of the oscillators closer together. This can be achieved if all the antennas are pointing radially inwards and their radiation reflected from a polygonal or other cylindrical mirror located through the center of the array; the

images of the phase centers of the antennas are now closer together and also closer to the array center.

An eight sector array using a octagonal cylindrical mirror with disks located above and below the array plane was designed using ray tracing techniques for operation at 28 GHz. The complete eight sector omni-directional array was not constructed but one, two and three sector arrays (45° per sector) were fabricated and tested. Injection locking from an external source was also implemented by placing a receiving patch antenna on each sector which was loosely coupled (-10 dB) to the sector oscillator [3]. Antenna pattern modelling based on the results of these experiments shows significant improvement in the azimuthal variation of the array being reduced to $\pm$ 2.9 dB for an eight sector array.

The array oscillators [7] used Raytheon InP HEMTs and followed the previous design but used a resonant Tee to increase the Q, making the oscillators less sensitive to device variations.

An array phase-noise model was developed [2,18], based on array dynamics theory combined with the phase-noise treatment of a single injection-locked oscillator. The results are expressed in a matrix equation describing the phase noise in arrays of arbitrarily coupled oscillators. Various common coupling schemes, as well as external injection-locking and phase-locked loops were also examined.

Quasi-Optical Monopole Probe Amplifier Arrays (Nick Kolias)

Free space power combining is demonstrated in an innovative, monopole based quasi-optical amplifier array. This planar solid state array is the culmination of extensive design and development of passive and active array prototypes at Ka and Ku-band [8,19]. Monoplole probe antennas are used to couple power from an incident beam into microstrip or coplanar waveguide transmission lines where the signal is amplified and the re-radiated in the

orthogonal polarization. Because the amplification takes place in a transmission line environment, standard solid state amplifiers may be used. Fabrication and characterization efforts involved passive and active versions of the array unit cell at 4 GHz, full passive arrays at 10 GHz and 35 GHz [10], and a 3 x 3 active array at 16 GHz.

The 4 GHz unit cell [22] was designed in stages by first optimizing a passive cell and then adding amplification sections to form the active cell. The unit cell was tested in a square waveguide set-up and had a measured gain of over 12 dB with a fractional bandwidth of 3.5% at 4 GHz.

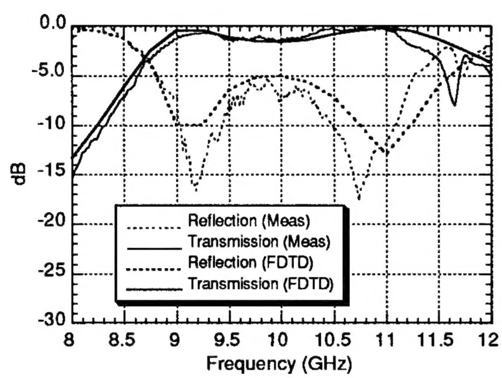


Figure 1. Reflection andtransmission measurements compared with FDTD model for a microstrip passive polarization rotator array at X-band.

Microstrip and coplanar waveguide passive polarization rotator arrays were developed 35 GHz (Ka-band), based on the unit cell design. This lead to an optimized microstrip passive array [8] exhibiting less than 1 dB of peak insertion loss and a 3 dB bandwidth of 22%. The CPW based array had a peak insertion loss of ≈ 2 dB and and a fractional 3 dB bandwidth of 7%. The superior performance of the former array led to the implementation of the active array in microstrip.

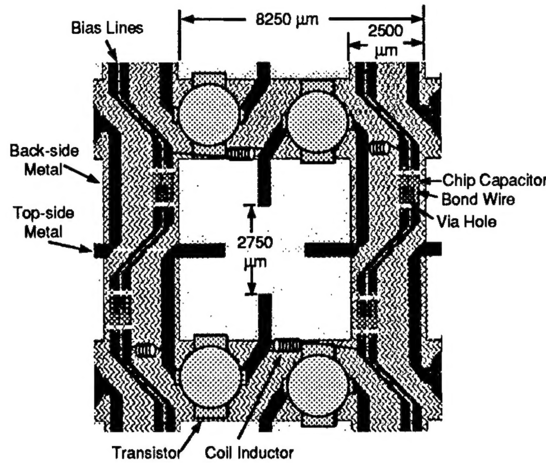


Figure 2. Optimized unit cell of the 16 GHz active array showing layout of transistors and bypass components. The wavy shaded region is the inductive mesh metallization on the backside of the array.

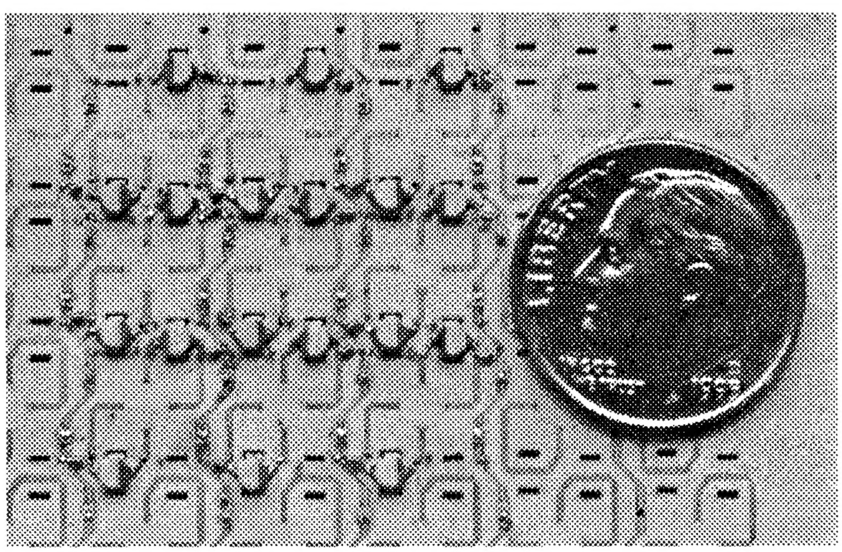


Figure 3. Close-up photograph of the completed 16 GHz active array.

The microstrip monopole probe planar array concept has been realized at Ku-band in a 3 x 3 amplifier array. The design was done in stages. First, the passive Ka-band design was scaled to lower frequencies and tested. This device exhibited excellent performance with

an insertion loss of less than 1 dB and a 3 dB bandwidth of 27.5%. As shown in Figure 1, these results agreed well with FDTD simulations [9]. Next, transistors were added to the passive structure after small modifications were made in order to insert biasing networks and to further isolate the active devices from each other. There is a fair correlation between the performance of the resulting active array and that of the passive array as the active array's peak gain frequency corresponds to a frequency of good polarization rotation (and small reflection) for the passive array.

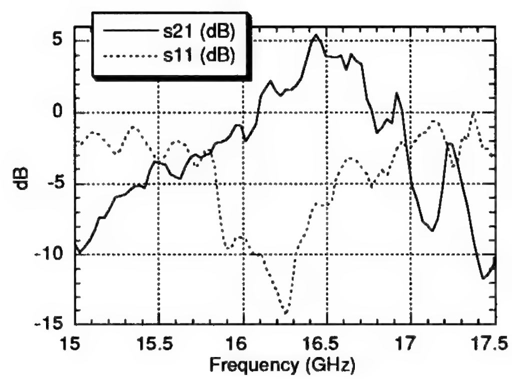


Figure 4. Gain and reflection coefficient plotted versus frequency for the 3 x 3 16 GHz amplifier array.

The active array was fabricated on a 20 mil thick Rogers TMM10 substrate using laser machining to produce vias and mounting holes for the packaged Fujitsu transistors (see Figures 2 and 3). Performance was evaluated using a focussed gaussian beam test range. At low and moderate bias levels no low frequency or parasitic oscillations were observed and the array was also tested for amplification linearity. A maximum gain of 5.4 dB with a 3-dB bandwidth of 2.4% centered at 16.4 GHz was achieved with these transistors which had s_{21} = 5.6 dB at 16.4 GHz. The gain versus frequency characteristics and the array reflection coefficient are shown in Figure 4.

Improved peformance would require further isolating the individual active elements to prevent the onset of oscillations under high bias conditions and improving the matching of the transistors to the monopole probe antennas.

Theoretical modelling of these arrays, including thermal modelling of the active array [11], was performed.

Quasi-Optical Array Analysis (Nick Kolias)

A modelling technique has been developed [12] for quasi-optical planar periodic array structures containing passive or active elements which are characterized by 4-port s-parameter measurements (two orthogonal polarizations at input and output). This technique has been applied to the microstrip monopole based arrays developed in this work to extract separately the s-parameters of the active and passive components in the array unit cell. These results have been compared with FDTD modelling results [19].

Q-PSK Modulation of Oscillator Arrays (Mark Vaughan)

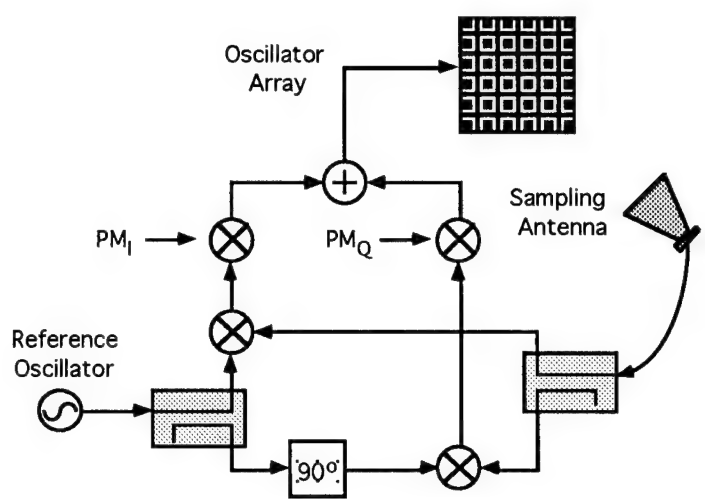


Figure 5. Quadrature PLL used to obtain full 360° of PSK from an oscillator array. Only a baseband signal is applied to the array, which operates as a VCO.

Using a novel phase locked loop (PLL) design, Q-PSK modulation of an array of oscillators can be implemented by creating quadrature branch paths in the feedback loop [13,18]. As shown in Figure 5, I and Q modulating signals are mixed into each branch (denoted PM_I and PM_Q), and the loop is completed by obtaining a signal from the array via a sampling antenna. This scheme allows modulation of the phase by a full 360° as required for standard Q-PSK. In the actual experiment a HP sweeper operating at 7 GHz, was used in place of an array and modulation rates of up to 1.5 Mbps were obtained. The quadrature PPL technique has been used to propose 16-QAM and higher order QAM implementations.

Phase-Shift Keying Modulator (Carlos Saavedra)

A phase-shift keying (PSK) modulator using a voltage-controlled oscillator array was designed, built, and tested at a carrier frequency of 28 GHz. To achieve M-PSK modulation, we used a dual PLL scheme (Figure 6) in which the signal from the reference oscillator was split into two components that were 90° out of phase [13]. These two signals were fed to a phase detector which compared the reference signals with the VCO output. The outputs of the phase detectors were modulated with the digital signals, summed, and then fed to the VCO input to close the loop.

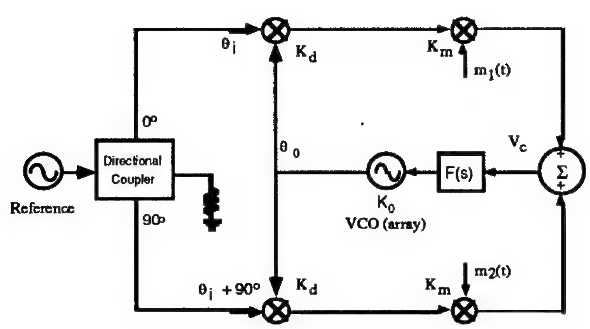


Figure 6. M-PSK modulator schematic. The thick lines represent high-frequency transmission lines, and the thin lines baseband connections.

For QPSK modulation, each of the two digital signals must have 2 voltage levels, for 8-PSK modulation each digital signal should have 3 voltage levels, and so on. The modulator built was capable of transmitting two different digital signals at data rates of 40 and 60 kbps (see Figure 7).

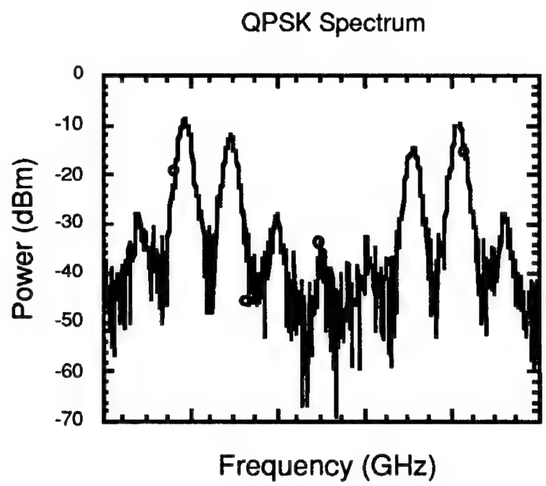


Figure 7. QPSK Spectrum. Center frequency: 28 GHz, frequency span: 100 kHz.

Time-domain computer simulations of the circuit in Figure 6 show that data rates in excess of 500 Mbps are possible with this circuit topology. One of the advantages of this circuit is that most of the modulation circuitry is at baseband so it can be built monolithically at a lower cost in silicon instead of GaAs.

Quasi-Optical Oscillator Arrays (Warren Wright)

Combining the output power of a large number of semiconductor sources may be achieved by direct coupling of source output to the modal fields of a Fabry-Perot resonator [23]. We have used reciprocity in our initial investigations of this technique [15]. Instead of using oscillator driven antenna arrays we have used arrays of passive receiving elements to measure the effects on a wave directed into the cavity. Arrays of $\lambda/2$ and $\lambda/8$ dipoles

resistively terminated with 90Ω resistors at the feedpoints were used and situated in the resonator (Figure 8) where the phasefront is near planar. The positioning of the array in the standing wave field was adjustable in the longitudinal direction. Both arrays showed significant interaction (change in s_{21}) when placed in the cavity which depended on the cavity resonance frequency and the array position in the standing wave field. The strongest interaction occurred with the $\lambda/8$ array which theory indicates has a much better match (100Ω) than the $\lambda/2$ dipoles (1000Ω). This contrasts with the behavior of the arrays when s_{21} is measured outside the cavity. These results were sufficiently supportive of the theory to proceed with active array experiments.

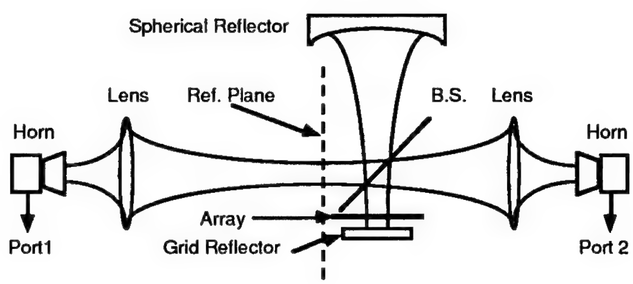


Figure 8. Quasi-optical range produces a fundamental gaussian beam with the waist at the reference plane. The transverse Fabry-Perot uses a beamsplitter to image this reference plane onto the wire grid reflector.

Several small arrays of pHEMT oscillators were fabricated as hybrid CPW circuits on 15 mil thick GaAs substrates designed for operation in the resonator at 28 GHz. The oscillators contained no resonant elements at or below the design frequency and each oscillator fed a very short slot antenna with a circuit electrical length of approximately ($\lambda/3$). When situated inside the standing wave field of the resonator it was expected the reactive component of the antenna impedance could be tuned and the resistive component transformed so as to form a good match to the pHEMT output matching network and to form a resonating

circuit when coupled to the Fabry-Perot resonator fields. The resonator consisted of a 75 mm focal length mirror and an inductive mesh coupler with 10% output coupling. These arrays oscillated at 14 GHz (close to the gate series resonant frequency for this transistor) when not situated inside the resonator and could be back-plane tuned over 1 GHz. When situated inside the resonator the increase in output power was very small (a few dB) and the expected antenna tuning behavior was not evident in degree or range, suggesting that significant coupling between the resonator fields and the antenna is not occurring. Coupling to other circuit elements (bond wires, discrete components etc) or the generation of surface wave modes by the antenna may be precluding the desired coupling mechanism. The arrays were also subject to device destruction, even at low drain-source voltages, due to high resonator field intensities or low frequency parasitic operation, which precluded further study of the behavior of this scheme. It was concluded that considerable design and modelling effort would be required for the pursuance of this scheme. A new and more promising array concept was developed at this time and is described in this report.

Quasi-Optical Test Range Measurements (Warren Wright)

In order to measure the reflectance and transmittance characteristics or the S-parameters of quasi-optical array devices, measurement techniques are being developed which can be applied to a wide range of test devices and structures. The basic test range set-up, shown in Figure 9 uses standard gain horns to launch and receive a beam which is close to a fundamental TEM_{00} free space gaussian beam. Rexolite or Teflon lens are used to focus the beam to a waist at the reference plane at the center of the range. Cross-polarization measurements are obtained by carefully rotating the horn and polarizer in one of the arms by 90° after calibration.

Since good calibration standards for free space throughs, shorts and matched loads are read-

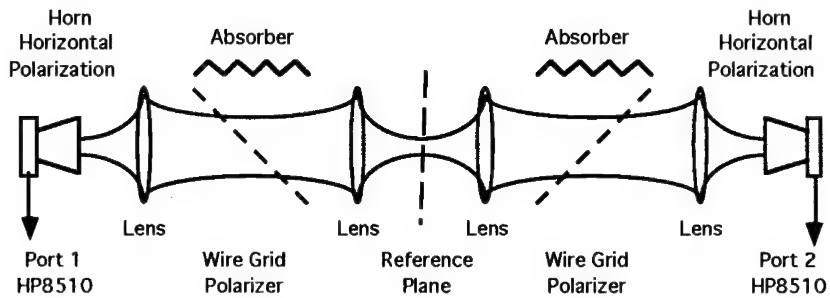


Figure 9. Quasi-optical copolar measurement range uses lens to form a beam waist at the reference plane.

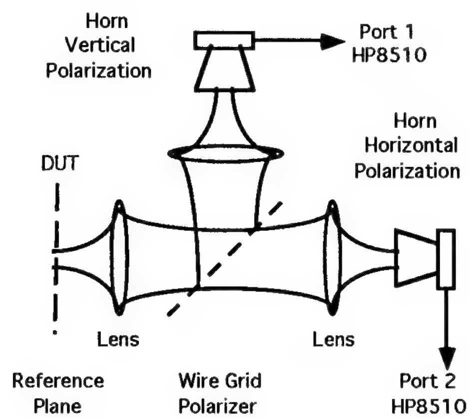


Figure 10. Quasi-optical reflect range can measure copolar and cross-polar reflection coefficients of a DUT situated at the reference plane.

ily made, LRM and full 2-port (one polarization) calibrations can be easily implemented. This applies also to the QO reflect range in Figure 10 which uses as a through standard a rooftop mirror to rotate the polarization at the reference plane during calibration. All 16 four-port S-parameters can thus be obtained using these two ranges.

Devices which can be measured with the above techniques include all thin ($\ll \lambda$) planar devices used at normal incidence. For these devices no significant distortion of the reflected

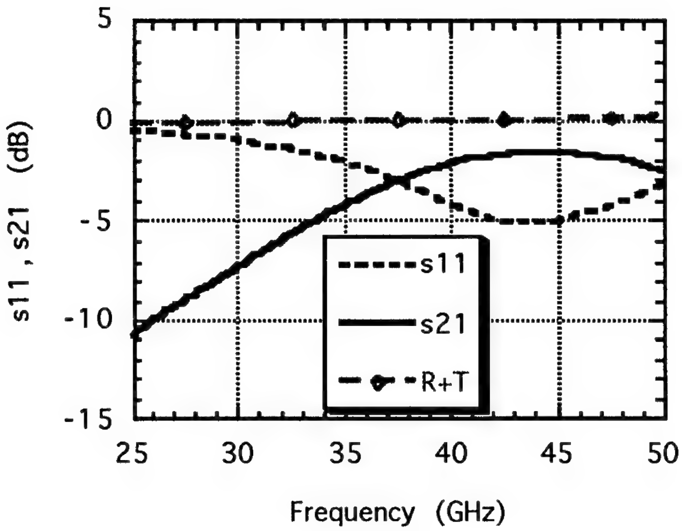


Figure 11. Inductive mesh S-parameter measurements performed using the quasi-optical measurement range calibrated using free space standards and the full two-port calibration procedure.

or transmitted beams occurs and the beam at the receiving horn has the same modal characteristics as the beam launched at the transmitting horn. In effect, the system is single mode and the beam is always in focus at the receiving horn. The effect of unwanted reflections from lens surfaces and mounting supports which are created when the DUT is introduced into the range (and therefore not eliminated during the calibration procedure) can be accurately eliminated by time domain gating. Results for a substrate supported inductive mesh, in Figure 11, show gated results. These results also show $|S_{11}|^2 + |S_{21}|^2 = 1$ to within experimental uncertainty as expected for a very low loss planar device. For thick quasi-optical devices or three-dimensional structures the dimension in the direction of propagation is sometimes large enough to cause a significant shift in the location of the beam waist at the receiving horn phase center. Further, the structure may launch new mode components into the receiving arm of the range. In these cases the calibrated measurement

procedures described above are no longer strictly valid. Compensation schemes, calibration procedures and innovative optical configuration techniques offer the means of overcoming some of these difficulties.

This work is continuing under the MAFET grant. We are continuing to develop new techniques suitable for the three-dimensional quasi-optical structures involved in that project.

Three Dimensional Grating Amplifier Arrays (Warren Wright)

One of the major problems with quasi-optical solid state arrays has been to efficiently bring free space energy into the active circuitry and then out again into free space. Traditional approaches have have been the grid approach, with active elements placed on an inductive grid; and the planar array antenna-input and/or antenna-output approach where each active element feeds and/or is fed by an antenna.

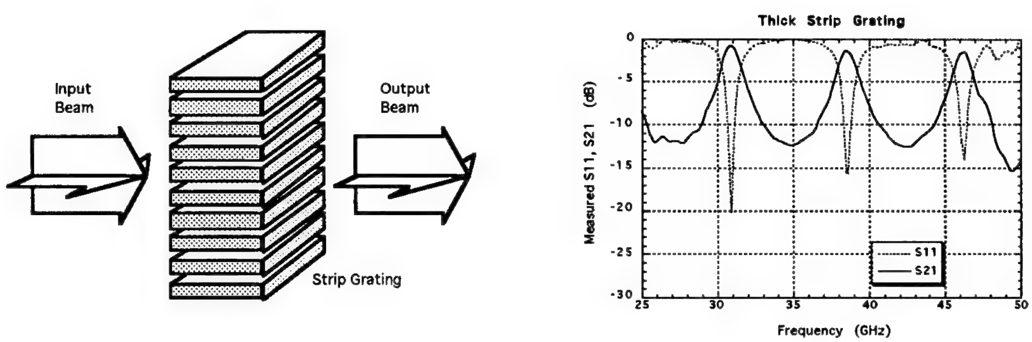


Figure 12. Strip grating structure with s-parameter results for a grating with period 3.1 mm, plate gap 0.5 mm and length 20 mm over the range 25 to 50 GHz.

A new concept in quasi-optical array design is being developed based on a three-dimensional waveguide grating structure [16]. This scheme utilizes radiating waveguide apertures making possible a new set of techniques for coupling free space beams into circuits with very low

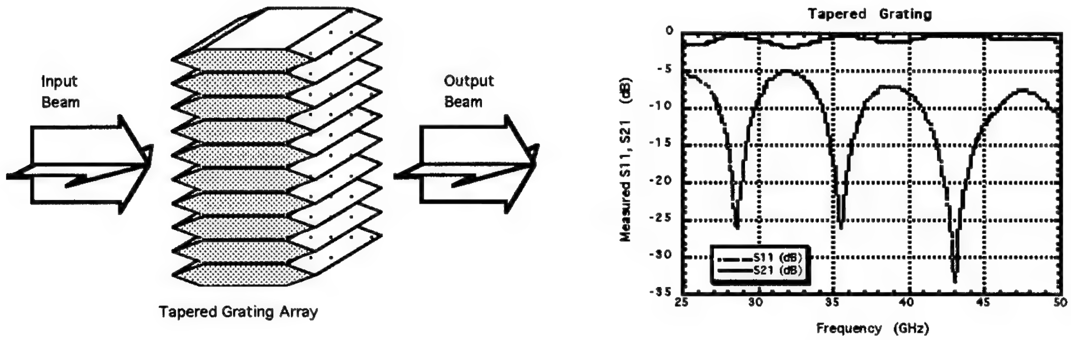


Figure 13. Tapered grating structure has tapered input and output sections added to the basic structure shown in Figure 12 and consequently exhibits much greater bandwidth.

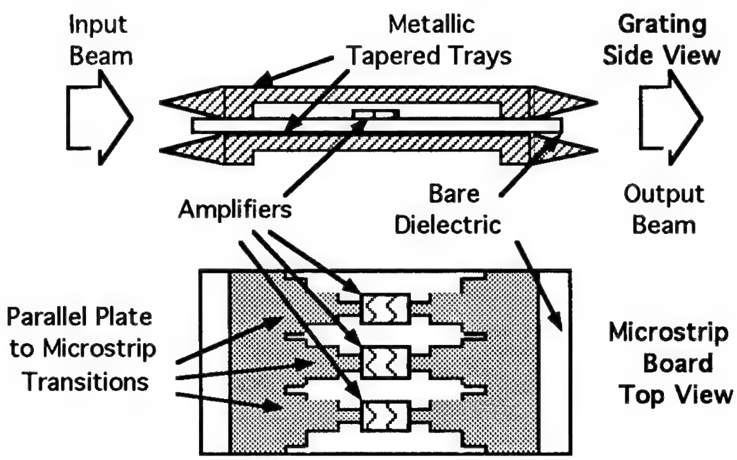


Figure 14. Tapered grating single layer section with circuit board containing parallel plate waveguide to microstrip transitions.

losses representing a significant improvement over the efficiencies characteristic of antennas on planar substrates.

The grating arrays pictured (Figures 12 and 13) consist of a stack of 11 blades or plates, separated by air gaps, forming 10 parallel plate waveguides spaced vertically with a period of approximately $\lambda/2$ at the highest frequency of interest.

A beam polarized vertically is normally incident on the structure. Since the gap spacing

between the plates is much less than $\lambda/2$ all TE and TM parallel plate modes are cutoff and only the TEM mode propagates through the structure.

As shown by the measurements in Figure 12, the structure depicted, a capacitive strip grating [24], has a high measured transmittance, theoretically 100%, at a series of resonance frequencies determined by the length of the grating in the direction of propagation. The 3 dB bandwidth is however, only 1.5 GHz or about 3%. By tapering the edges of the plates to form a tapered grating structure the transmittance can be improved and the bandwidth can be greatly increased as shown by the measurements in Figure 13. The transmittance loss is less than 2 dB over the 25 GHz range. These results are in good agreement with theoretical models of these structures. A manuscript on this work is being prepared [16].

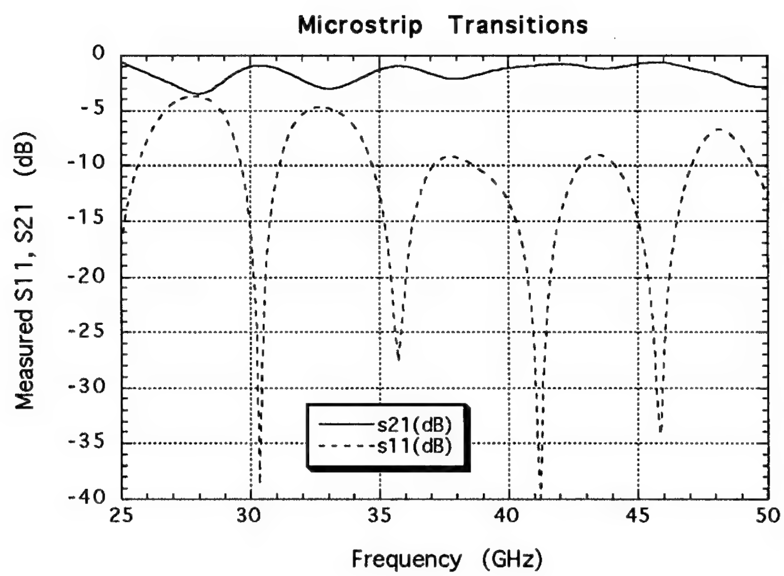


Figure 15. Measured s-parameters for the tapered grating containing microstrip circuit boards with 50Ω through transmission lines.

These stuctures can be used to amplify the transmitted wave by appropriately mounting

active devices inside the parallel plate region. Experiments have been made using passive circuits. In Figure 14 a single layer of the tapered grating is shown with a circuit board patterned with parallel plate to microstrip transitions. The measured s-parameters for a grating array consisting of 10 layers of circuit board with each board having 10 microstrip sections are shown in Figure 15.

This device has a minimum S_{21} of $\leq$ 1.0 dB over a 7 GHz bandwidth. These results show that parallel plate gratings can be expected to be simple, reasonablely efficient, large bandwidths structures suitable for coupling free space millimeter wave beams into microstrip circuits. By their physical architecture these structures can also be expected to possess good heat sinking capabilities when used with power devices and to provide good rf circuit isolation between individual active elements.

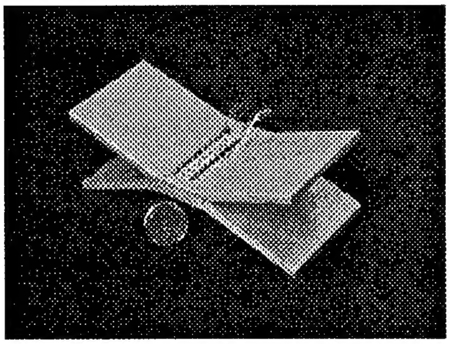
This work is being continued under a MAFET grant.

Quasi-Optical n x 1 Amplifier Array (Carlos Saavedra)

An n x 1 amplifier array for operation at 44 GHz is being developed using pHEMT power chips [17]. The chips are situated adjacently inline on a microstrip board. Each chip input is transitioned to an input parallel plate waveguide formed before the input flared section of the horn (Figure 16). The parallel plate separation is much less than $\lambda/2$ so that only the TEM mode can propagate after a few millimeters of parallel plate section. The output transitions are similar to the input transitions.

We have designed and tested the passive structure in which the active elements were replaced by microstrip through lines in order to determine the system losses. The flare angle of the inclined plane horn antennas is 35° and was chosen by constructing antennas of different angles, and selecting the one that gave the best results at 44 GHz.

The microwave substrate material used was TMM3 from the Rogers Corp., which has a



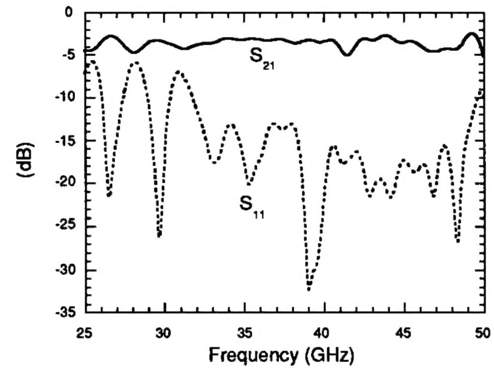


Figure 16. Single layer array amplifier uses a tapered horn to couple from free space to a row of parallel microstrip pHEMT amplifier cells. Measurements show s-parameters for passive microstrip through circuits.

dielectric constant of 3.27. Measurements on the passive structure were made from 25 to 50 GHz using a gaussian beam test setup. The array shows an average insertion loss of -3.6 dB. Without the microstrip circuit the system shows an average insertion loss of -2.2 dB, implying that only -1.4 dB of loss is incurred in the power splitting and combining circuitry. The active array was under construction at the end of this Reporting period.

4.C List of Publications

[1] M. J. Vaughan, R. C. Compton, S. Duncan, D. Tu, and S. Weinreb, *Monolithic, W-band, Voltage-Controlled Oscillator*, IEEE MTT-S International Microwave Symposium Digest, Vol. 1 pp. 337-340, June 1996.

[2] M. J. Vaughan, and R. C. Compton, *Phase Noise in Arrays of Mutually-Coupled Oscillators and its Reduction via Injection-Locking and PLLs*, submitted to IEEE Trans. MTT, October 1995.

[3] M. J. Vaughan, and R. C. Compton, *Injection-Locked 28 GHz Oscillator Array with Disk-Cylinder Reflector*, IEEE Microwave and Guided Wave Letters, **6**, pp 196-198, October

1995.

[4] M. J. Vaughan, and R. C. Compton, *28 GHz Oscillator for Endfire Quasi-Optical Power-Combining Arrays*, Electronics Letters **31**, pp 1453-1455, 1995.

[5] M. J. Vaughan, and R. C. Compton, *28 GHz Omni-Directional Quasi-Optical Transmitter Array*, IEEE Trans. MTT, **43**, pp. 2507-2509, October, 1995.

[6] M. J. Vaughan, and R. C. Compton, *Improved Radiation Pattern for 28 GHz Omni-Directional Quasi-Optical Oscillator Array*, 1995 IEEE AP-S Int. Symp. Dig., pp. 1372-1375, June 1995.

[7] M. J. Vaughan, R. C. Compton, Katerina Y. Hur, and Rebecca A. McTaggart, *InP-Based 28 GHz Integrated Antennas for Point-to-Multipoint Distribution*, IEEE/Cornell Conference on Advanced Concepts in High Speed Semiconductor Devices and Circuits, August 1995.

[8] N. J. Kolias, and R. C. Compton, *A Microstrip-Based Quasi-Optical Polarization Rotator Array*, IEEE MTT-S Int. Microwave Symp. Dig., pp. 773-776, May 1995.

[9] A. Alexanian, N. J. Kolias, R. C. Compton, and R. A. York *Three-Dimensional FDTD Analysis of Quasi-Optical Arrays Using Floquet Boundary Conditions and Beringer's PML*, IEEE Microwave and Guided Wave Letters, **6**, pp 138-140, March 1996.

[10] N. J. Kolias, and R. C. Compton, *A 35 GHz CPW-Based Antenna Array for Quasi-Optical Amplifiers*, 20th International Conference on infrared and Millimeter Waves, Orlando FL, December 1995.

[11] N. J. Kolias, and R. C. Compton, *Thermal Management for High Power Active Amplifier Arrays*, IEEE Trans. MTT, **44**, pp 963-966, June 1996.

[12] N. J. Kolias, A. Alexanian, R. A. York, and R. C. Compton, *Parameter Extraction for Quasi-Optical Amplifier Arrays*, 1996 National Radio Science Meeting Digest, Jan., 1996.

[13] C. E. Saavedra, M. J. Vaughan, and R. C. Compton, *An M-PSK Modulator for Quasi-*

Optical Wireless Array Applications, MTT-S Int. Microwave Symposium Digest, vol. 3, pp. 1243-1246, 1996.

[14] M. J. Vaughan, W. Wright, and R. C. Compton, *Active Antenna Elements for Millimeter-Wave Cellular Communications*, International Symposium on Signal, Systems, and Electronics, San Francisco CA, October 1995.

[15] W. Wright, and R. C. Compton, *Power Combining of an Array of Sources with Electrically Short Dipole Antennas in a Fabry-Perot Resonator*, 20th International Conference on infrared and Millimeter Waves, Orlando FL, December 1995.

[16] C. E. Saavedra, W. Wright, and R. C. Compton, *Three-Dimensional Gratings for Millimeter Wave Applications*, manuscript in preparation for submission to IEEE Trans. MTT.

[17] C. E. Saavedra, W. Wright, and R. C. Compton, *A Passive Horn Structure with Transitions to Microstrip for Quasi-Optical Amplifier Arrays*, submitted to the 4th International Millimeter and Submillimeter Wave Conference, San Diego, California, 1998.

4.D Scientific Personnel

Richard Compton, Mark Vaughan, Rene Martinez, Nick Kolias, Carlos Saavedra, Warren Wright.

Graduating Personnel:

Mark Vaughan Ph.D. Cornell University, May 1996

Nick Kolias Ph.D. Cornell University, August 1996

Theses: *Note*: reference numbering continues on from above section.

[18] M. J. Vaughan, *Millimeter-Wave Oscillators and Power-Combining Arrays for Commercial Wireless Applications*, Ph.D. dissertion, Cornell University, May, 1996.

[19] N. J. Kolias, *Monopole Probe Based Millimeter-Wave Quasi-Optical Amplifier Arrays*, Ph.D. dissertion, Cornell University, August, 1996.

5. Inventions, Patents

Patent: R. D. Martinez, and R. C. Compton, *Method and Apparatus for Spectrum Sharing between Satellite and Terrestrial Communications Services using Temporal and Spatial Synchronization*, U.S. Patent number 5,584,046.

6. Bibliography

Note: reference numbering continues on from above section.

[20] M. J. Vaughan, R. C. Compton, and S. Weinreb, *Monolithic 60 GHz PHEMT Oscillator*, 1994 URSI Radio Science Meeting, Seattle, WA, June 1994.

[21] M. J. Vaughan, and R. C. Compton, *Resonant-Tee CPW Oscillator and the Application of the Design to a Monolithic Array of MESFETs*, Electronics Lett., **29**, pp. 1477-1479, August 1993.

[22] N. J. Kolias, and R. C. Compton, *A Microstrip-Based Unit Cell for Quasi-Optical Amplifier Arrays*, IEE Microwave Guided Wave Lett., **3**, pp. 330-332, September 1993.

[23] J. T. Mink, *Quasi-Optical Power Combining of Solid-State Millimeter Wave Sources*, IEEE Trans. MTT, **34**, pp.273-279, 1986.

[24] R. C. Compton, L. B. Whitbourn, R. C. McPhedran, *Strip gratings at a dielectric interface and the application of Babinet's principle*, Appl. Optics, **23**, 3236-3242, 1984.